ION OPTICAL DESIGN OF SIS100 AND SIS300*

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Abstract

SIS100 will provide high intensity ion beams of all species from protons to uranium up to a magnetic rigidity of 100 Tm. The ion optical layout is optimized for acceleration of heavy ions with intermediate charge state (e.g. U^{28+}). Intermediate charge states are required to minimize space charge effects and to reach the necessary heavy-ion intensities for the FAIR project. Operation with intermediate charge states requires a specific lattice cell layout providing a separation of the ions after loosing an electron from the circulating beam. A charge-separator-like lattice layout provides a peaked loss distribution which is suitable for an effective catcher system.

SIS300 will provide beams of highly charged heavy ions (e.g. U^{92+}) with a maximum rigidity of 300 Tm. In addition it will function as a stretcher ring for SIS100 with a maximum rigidity of 100 Tm. In order to place the two synchrotrons in the same tunnel, the ion optical layout has to match the geometrical shape of SIS100. The presented beam transfer system from SIS100 to SIS300 is designed for the tight conditions in a single straight section of the two machines. The main superconducting magnets of SIS300 are supposed to produce time dependent field errors due to persistent currents. To compensate these transient effects the ion optical setting has to be corrected with an effective feedback system.

SIS100

U^{28+} is the design ion of SIS100. Nevertheless within the FAIR project [1, 2] all ion species from Protons to Uranium will be accelerated. The existing GSI accelerators UNILAC [3] and SIS [4] are used as injectors for SIS100. By eliminating one stripper stage of the existing accelerator complex the ion intensity can be increased by a factor of about seven. In addition the space charge in the resulting beam is reduced due to the lower charge state. However ions of intermediate charge have high cross sections for charge exchange reactions. Collisions of the beam ions with residual gas molecules change their charge state and consequently cause beam loss behind the next dispersive lattice elements. Due to the ion impact on the beam tube additional gas is desorbed leading to an amplification of the ionization process. This avalanche effect generated by the vacuum dynamics has to be avoided by minimizing and controlling the ionized particles. The SIS100 lattice is designed to have a peaked loss distribution for ions undergoing a charge exchange. Each lattice cell acts as a charge separator and ions are lost at dedicated scarpers with low desorption rates and high pumping power in the vicinity (for details on dynamic vacuum effects see[5]).

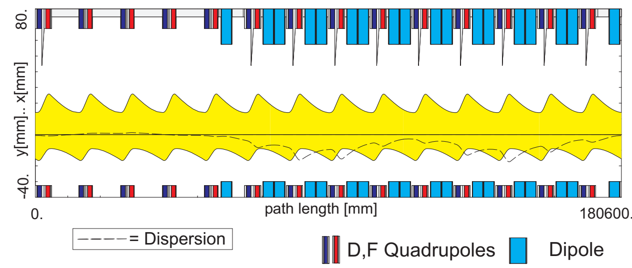

Figure 1: SIS100 lattice with the basic layout of one full sector or sextant with 14 lattice cells. The beam envelopes are shown for a beam emittance of e_h = 34 mm mrad in the horizontal phase plane and e_v = 14 mm mrad in the vertical phase plane respectively. The dispersion function is plotted for a momentum deviation of dp/p=1% and the ion optical functions for the tune setting Q_h=18.82 and Q_v=18.80.

Table 1: Parameter table for the SIS100 and SIS300

		SIS 100	SIS 300
Machine circumference	[m]	1083.6	1083.6
Magnetic rigidity B	[Tm]	100	300
Magnet field B	[T]	1.9	4.5
Bending radius ρ	[m]	52.632	66.667
No. of lattice cells NF		6·14	6·7
Len. of lattice cell LF	[m]	12.90	25.80
No. of DP magnets		108	48+12
No. of QP magnets		168	84
DP bending angle	[°]	$3\frac{1}{3}$	$6\frac{2}{3}+3\frac{1}{3}$
DP magnets per sextant		8·2+2·1	8·1+2·1
Straight sections		4·LF	2·LF

In addition to the local control of ioninisation losses the lattice is designed to fulfill the following requirements:

- large horizontal and vertical machine acceptance at moderate magnet apertures,
- adequate free space in the six straight sections,
- variable dispersion setting in the straight sections with the option to set zero dispersion for the fast extraction of bunches with large momentum spread and to generate sufficient dispersion required for the Hard conditions at slow extraction,

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Table 2: Ion optical parameters for the three working points of SIS100.

Workingpoint	WP2	WP1	WP3
Tunes (h/v)	17.42 / 17.36	18.84 / 18.73	20.84 / 20.73
Mode of SIS100 operation	Ions, slow extraction	Ions, fast extraction, bunch compression	high energy Protons, fast extraction, bunch compression
Max. β-function (h/v) (m)	19.9 / 19.5	19.6 / 19.6	20.4 / 19.9
Dispersion function			
Maximum α_p (m)	1.44	1.73	1.30
Minimum α_p (m)	-1.01	-0.13	-0.34
Phase advance per lattice cell (deg)	75 / 74	81 / 80	89 / 89
Transition energy	14.27	15.59	17.48
Natural chromaticity ξ_{nat}/Q (h/v)	-1.17 / -1.16	-1.19 / -1.2	-1.25 / -1.26
Transverse acceptance (h/v) (mm mrad)	200 / 54	206 / 54	203 / 53

- high compatibility with the layout of SIS300 to optimize the installation and operation of both synchrotrons in the same tunnel.

Table 1 summarizes the basic parameters of the SIS100 lattice. The machine circumference of 1083.6 m is five times the circumference of the existing booster synchrotron SIS18. The maximum magnetic rigidity of Bρ = 100 Tm is reached at a dipole field of B = 1.9 T. In each sextant the SIS100 lattice is composed of 14 lattice cells with a length of 12.90 m, i.e. each sextant has 10 lattice cells in the arcs, eight with two dipole magnets and at each side one cell with only one dipole magnet, and in the straight section four lattice cells with a total length of 51.60 m. The missing magnet scheme was chosen with respect to the dispersion setting in the straight sections (see Figure 1 for the basic lattice layout).

In each regular lattice cell two dipole magnets, each with 3.062 m effective field length, and two quadrupole magnets, each with 1.3 m effective field length, are arranged in a doublet focusing scheme (BM,BM,D,F). Their structure leaves sufficient space of more than 5 m for installation of steering magnets, sextupole magnets, multipole corrector magnets and beam position monitors. The doublet focusing structure in the scheme D, F was chosen to obtain adequate transverse acceptance and to achieve a high scarper efficiency for operation with U^{28+}-ions.

In the straight sections, a very small dispersion in the range of 0.2 to 0.4 m depending on the tune setting, can be achieved. This should be adequate even for machine operation in the bunch compressor mode with a maximum momentum spread of dp/p=1%, resulting in a beam broadening of 2-4 mm in the straight sections.

Table 2 summarizes the ion optical parameters for three different tune settings of the SIS100 lattice. For standard operation with ions, fast extraction and bunch compression it is proposed to use the tune setting at working point WP1 with Q_h/Q_v=18.84/18.73. The lower working point WP2 with Q_h/Q_v=17.42/17.36 was introduced for slow extraction providing the necessary momentum dispersion for the setup of the Hardt condition. The third working point WP3 at Q_h/Q_v=20.84/20.73 is used at proton acceleration to high energies.

Acceleration of proton beams to the maximum energy of 29 GeV requires crossing of the transition energy at γ_t=17.48. In order to avoid transition energy crossing the well-proven operation scheme, as demonstrated in the existing SIS18, introducing a dynamic shift of the transition energy at acceleration will be applied. Since the transition energy is determined by the integral over the dispersion function inside all dipole magnets, γ_t can be moved dynamically to values beyond the maximum proton energy of about $\gamma_t \approx 32$ by an adequate adjustment of the dispersion function. This special optical setting can be realized by separating F quadrupole magnets to two families, while keeping only one family of D quadrupole magnets. The regular symmetric setting of the quadrupoles will be reproduced at the end of the acceleration cycle to prepare for beam compression and beam extraction. During the change of the ion optical setting from the high transition energy γ_t = 44 to the regular transition energy γ_t = 17.48 the proton beam crosses the transition energy at $\gamma_t \approx 32$. However, this procedure occurs at constant beam energy where the voltage amplitude of the RF system can be reduced to avoid blow up of the longitudinal phase space.

SIS300

SIS300 has to fulfill two roles within the FAIR project. First it will be used as a high energy synchrotron to provide heavy ion beams for the CBM experiment with rigidities up to 300 Tm. In addition, SIS300 will be used as a stretcher ring for all experiments requiring a slowly extracted cw-like SIS100 beam. The maximum rigidity in the stretcher mode is 100 Tm defined by SIS100. In both modes of operation SIS100 will operate as injector for SIS300.

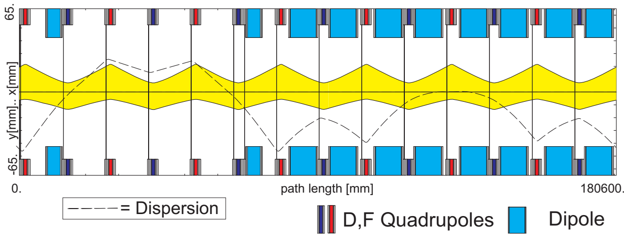

Figure 2: SIS300 lattice with the basic layout of one full sector or sextant with 7 lattice cells. The beam envelopes are shown for a beam emittance of ϵ_h = 10 mm mrad in the horizontal phase plane and ϵ_v = 4 mm mrad in the vertical phase plane respectively. The dispersion function is plotted for a momentum deviation of dp/p=1% and the ion optical functions for the tune setting Q_h=13.2 and Q_v=9.80.

The main requirements for the SIS300 lattice design are:

- The geometrical layout of SIS300 has to follow the SIS100 design. Both synchrotrons share the same tunnel.
- The SIS300 lattice has to be able to deliver slowly extracted beams with spills of up to 100 s. The beam transport of the extracted beams to the surface is situated in the same tunnel with the SIS100 beam (see [6] for details on the SIS100 and SIS300 extraction systems).
- The beam transfer from SIS100 to SIS300 has to be realized in the vertical plane within one straight section of the two machines.

To place SIS300 on top of SIS100 in the same tunnel, curved cos(θ)-magnets with a maximum dipole field of 4.5 T are foreseen for SIS300. For precise matching of the geometrical shape of SIS100, half length dipoles are placed at the ends of each arc. SIS300 is designed with a FODO focussing scheme. The length of each FODO half-cell matches the 12.9 m of a SIS100 regular lattice cell. This structure centers each single SIS300 quadrupole magnet with respect to the SIS100's quadrupole doublets. See Figure 2 for the basic layout of one sextant.

Table 3: Ion optical parameters of SIS300.

Tune (h/v)	13.2 / 9.8
Extraction	slow extraction
Maximum α_p (m)	4.8 m
Transition energy γ_t	9.25
Natural chromaticity ξ_{nat}/Q (h/v)	-1.35 / -1.14
Acceptance (h/v) (mm mrad)	51 / 44

The basic parameters of the SIS300 lattice can be found in the Tables 1 and 3. The dipole magnets are moved slightly towards the defocussing quadrupole magnets to increase the horizontal acceptance of the synchrotron.

BEAM TRANSFER FROM SIS100 TO SIS300

To gain additional space for the transfer focussing system, the first three kicker modules are placed in the missing dipole gap at the end of the arc of SIS100. The beam is deflected upwards downstream the first quadrupole doublet of the straight section. A pair of two magnetic septa are used for extraction. The first septum has a very thin blade of 8 mm and a field of 0.8 T and an effective field length of 0.5 m. The second strong septum magnet has a field strength of 1.67 T. This design provides the length of one regular lattice cells (12.90 m) for the transfer focussing system. Two superferric quadrupoles and four warm quadrupoles are used to match the beam from the SIS100 doublet to the FODO focussing structure of SIS300. The beam is deflected onto the SIS300 optical axis by a single magnetic septum. A nearly perfect transverse matching can be achieved. The transfer system leaves space for beam diagnostics and an optional stripper stage.

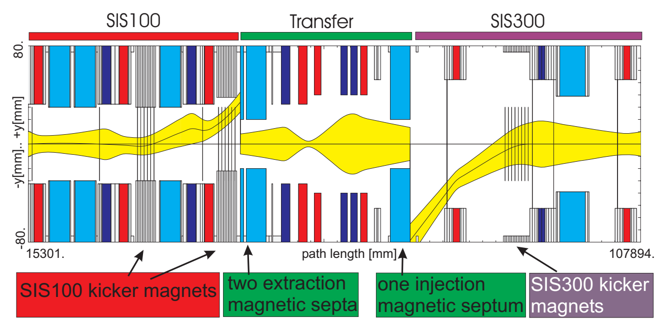

Figure 3: Layout of the beam transfer from SIS100 to SIS300. The beam is kicked upwards by a fast kicker system and extracted by two septum magnets. The focusing system of the transfer optics consists of two cold SIS100 and four warm quadrupole magnets. The beam is injected into SIS300 by one septum magnet and kicked back to the closed orbit.

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